Atmospheric Mining in the Outer Solar System: Outer Planet Orbital Transfer and Lander Analyses

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Introduction

- **Why atmospheric mining?**
- **Resource capturing: helium 3, hydrogen, helium.**
- **Orbital transfer vehicle (OTV), lander, factory sizing.**
- **System optimization(s) and issues.**
- **Observations.**
- **Concluding remarks.**

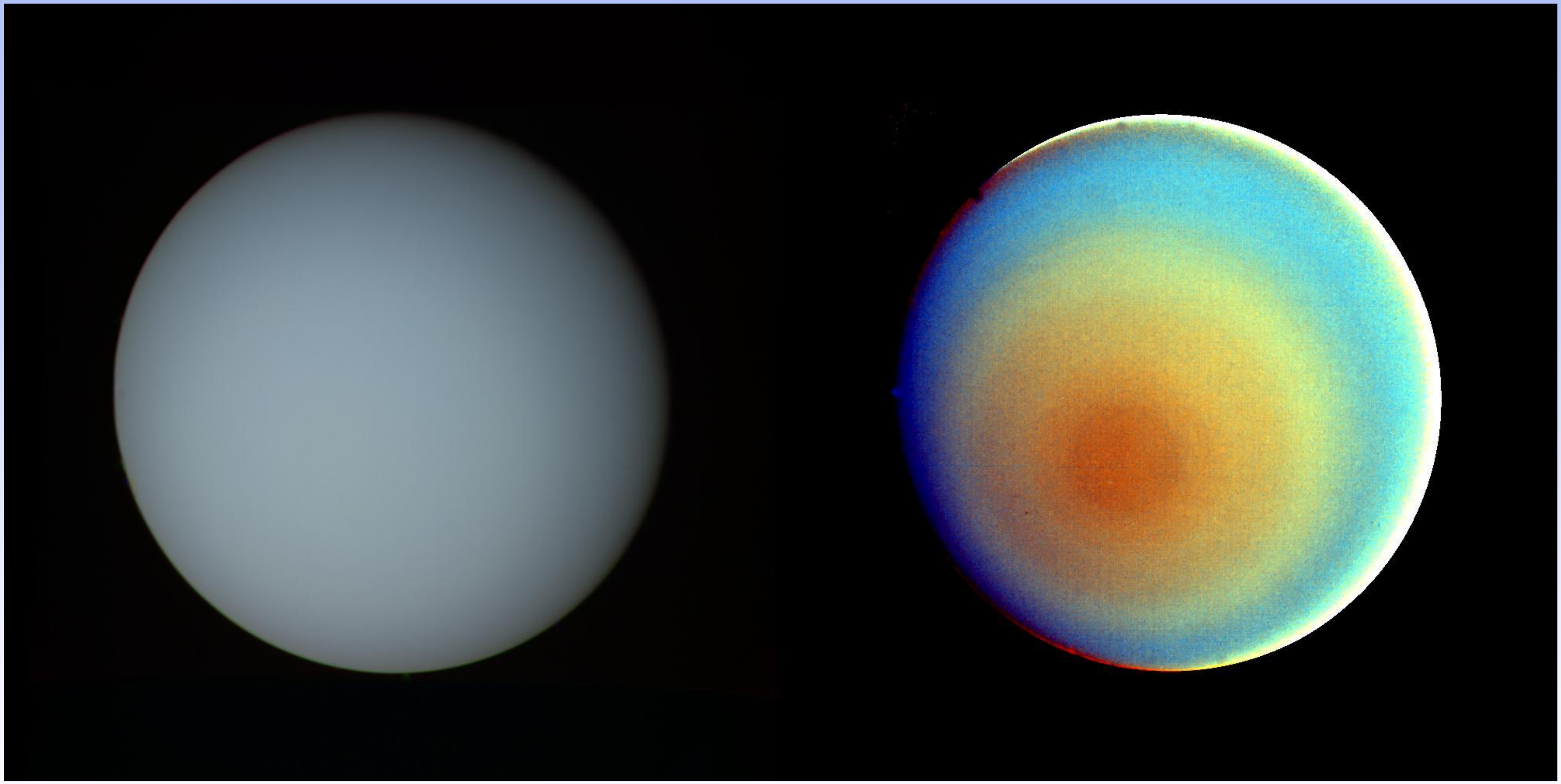
In Situ Resource Utilization (ISRU)

- In Situ Resource Utilization uses the materials from other places in the solar system to sustain human exploration
- Using those resources reduces the reliance on Earth launched mass, and hopefully reduces mission costs
- There are powerful capabilities to free humans from Earth

Why Atmospheric Mining?

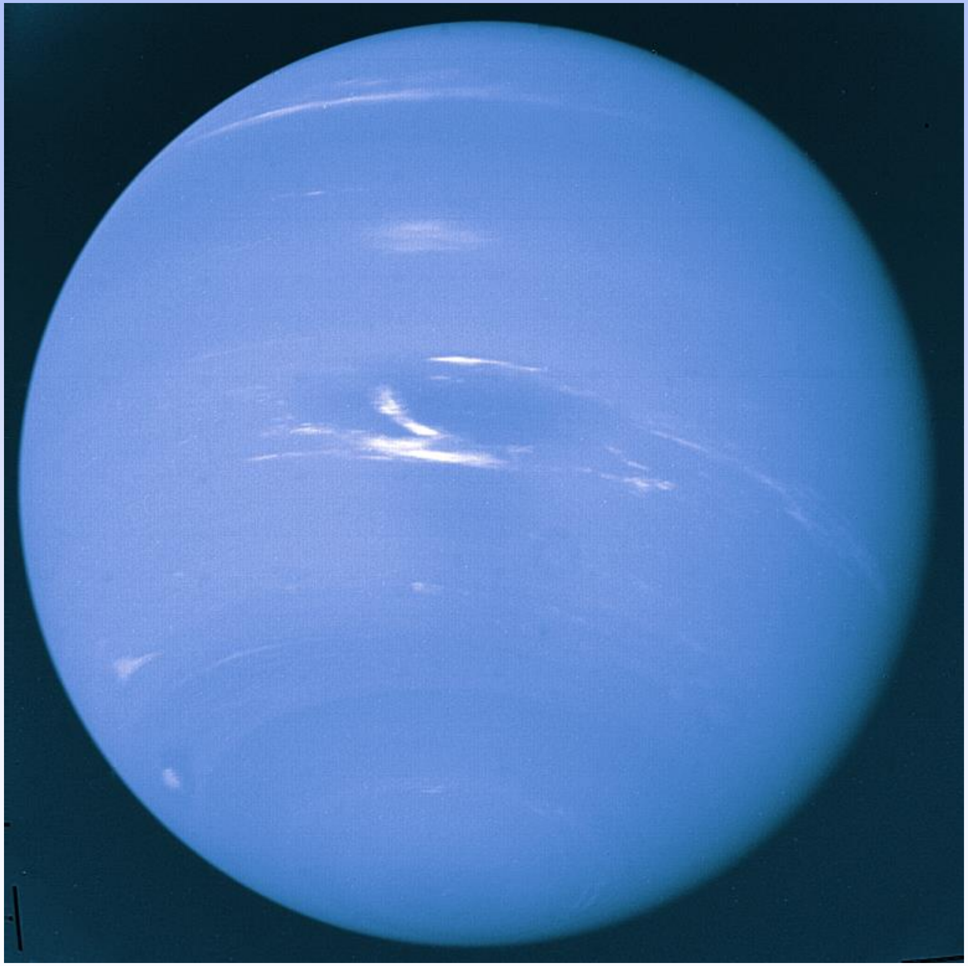
- **Benefits:**
  - Large amount of matter to mine (hydrogen and helium 3)
  - Potentially easier than mining regolith (dust) and rock
  - Larger reservoir of materials not readily available in regolith (and in a gaseous state)
- **Potential drawbacks**
  - Dipping deep into the gravity well of planets is expensive for propulsion systems
  - Lifetime of systems
  - Repetitive maneuvers
  - Cryogenic atmospheric environments
  - Long delivery pipelines

Uranus



JPL

Neptune



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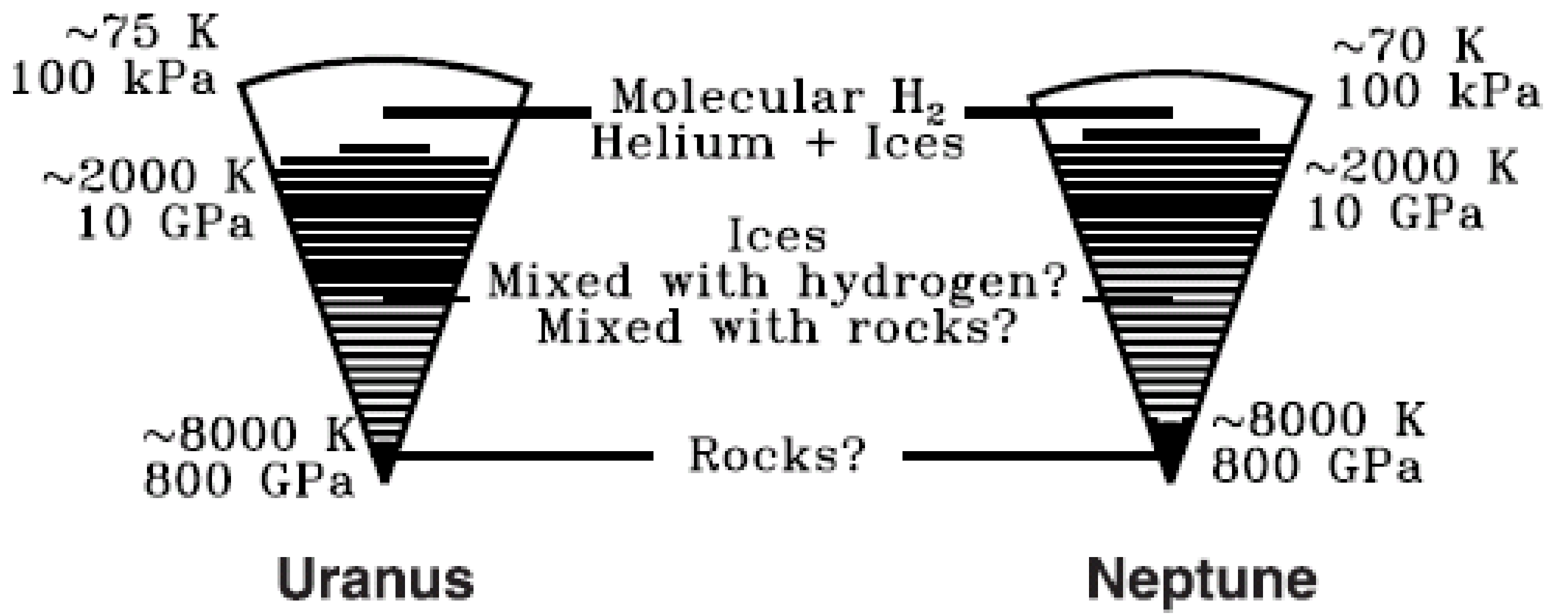
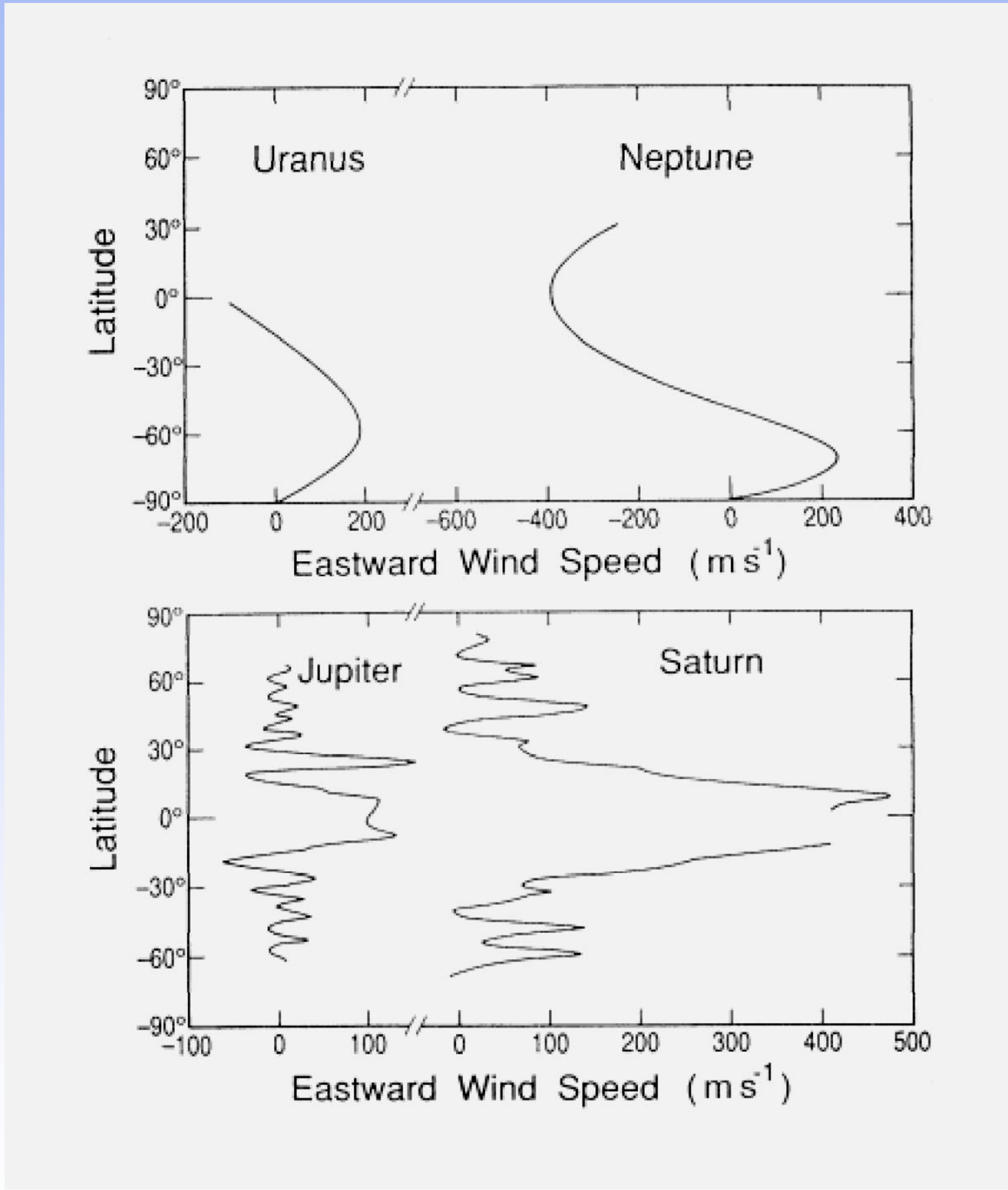
Outer Planet Atmospheres



Tristan Guillot, "Interiors of Giant Planets Inside and Outside the Solar System."

Outer Planet Atmospheres and Wind Speeds

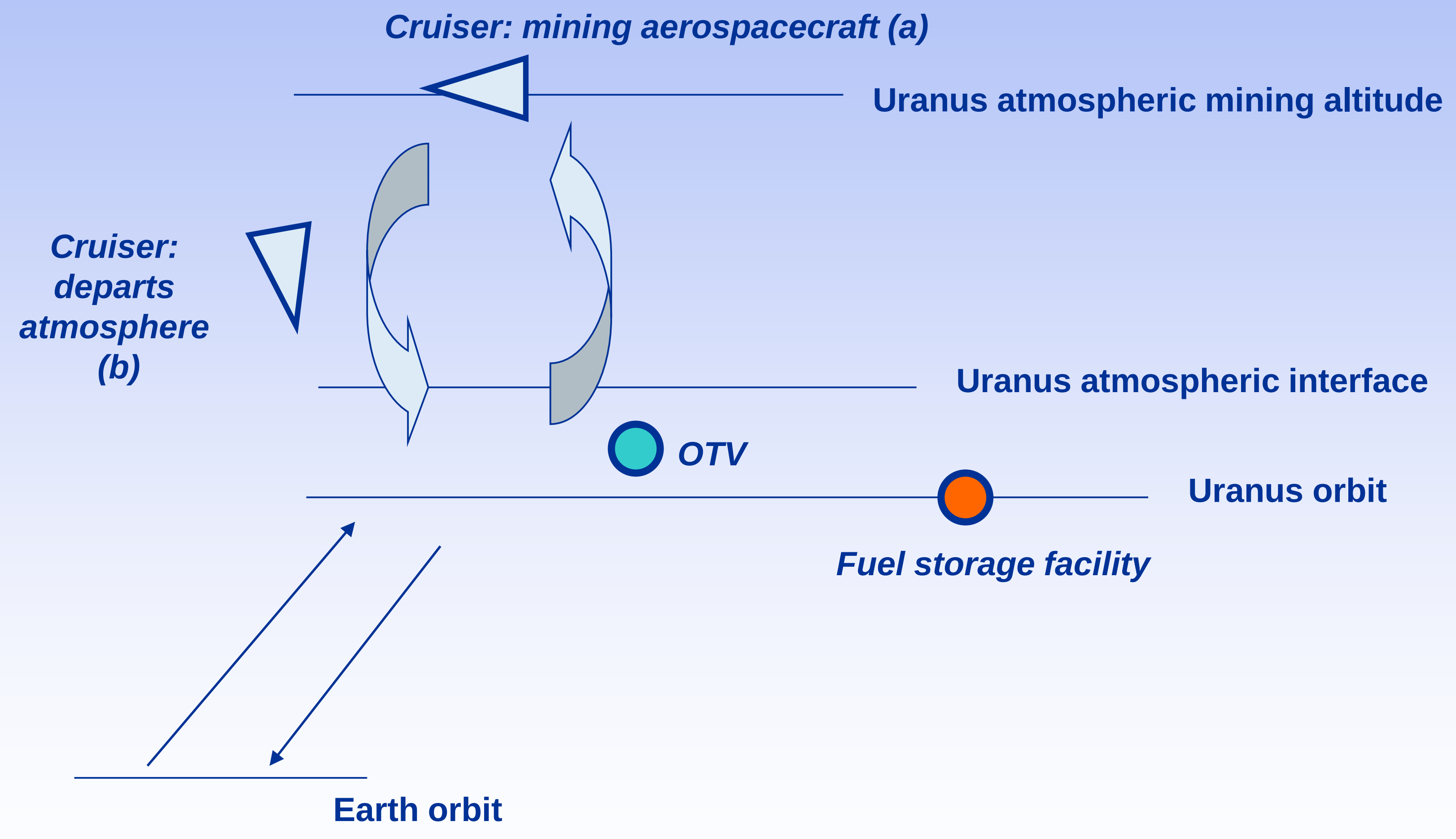


JPL, Ingersoll

Orbital Velocities: 10 km altitude

Planet	Delta-V (km/s)	Comment
Jupiter	41.897	BIG
Saturn	25.492	BIG
Uranus	15.053	More acceptable
Neptune	16.618	More acceptable

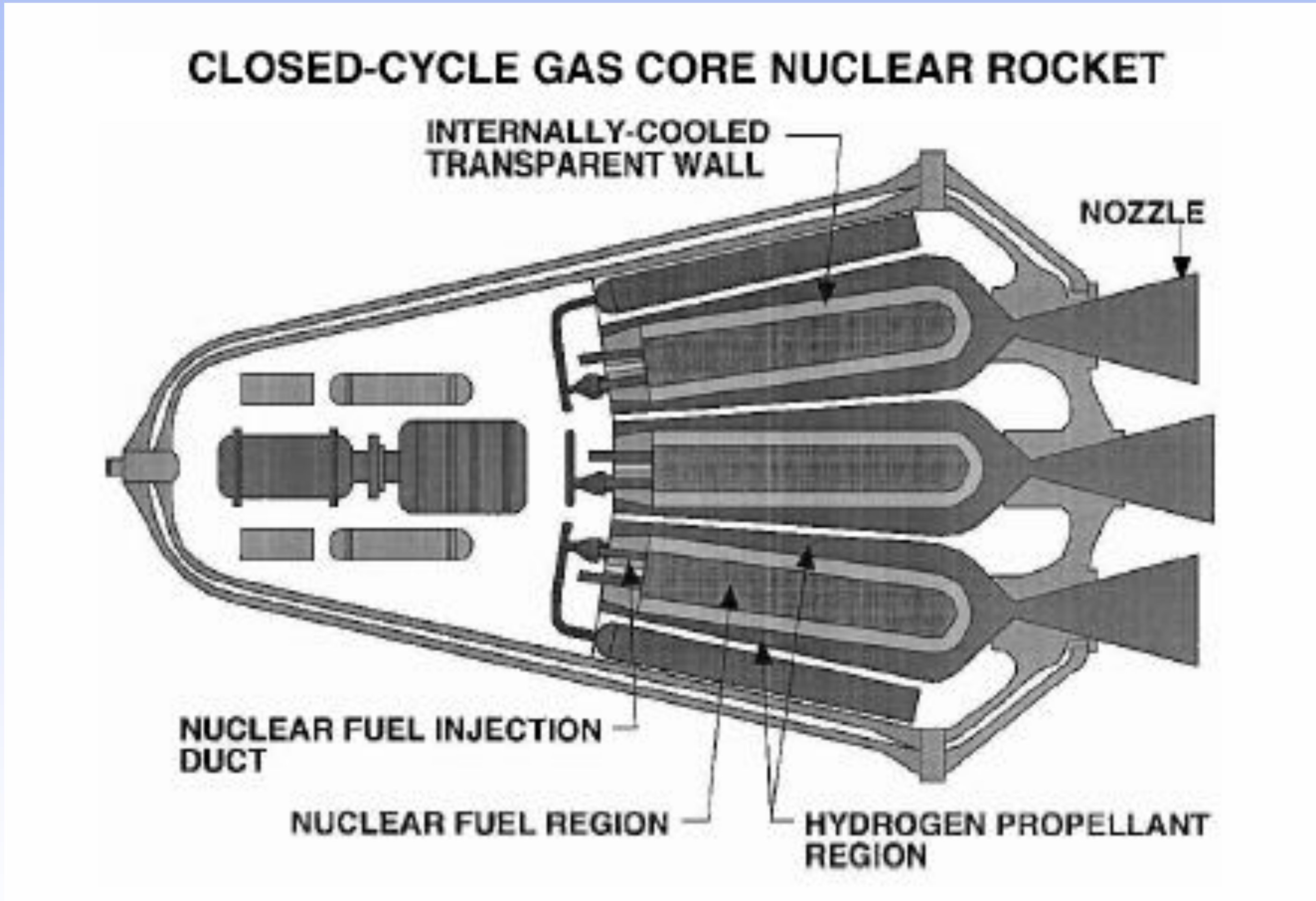
Cruiser Mining (1)
Combined Miner and Aerospacecraft



Mining Scenarios and OTVs

- Using cruiser aerospacecraft for mining in the atmosphere at subsonic speeds.
- Cruiser aerospacecraft then ascends to orbit, transferring propellant payload to orbital transfer vehicles (OTV).
- OTV will be the link to interplanetary transfer vehicle (ITV) for return to Earth.
- Moon bases for a propellant payload storage option was investigated.

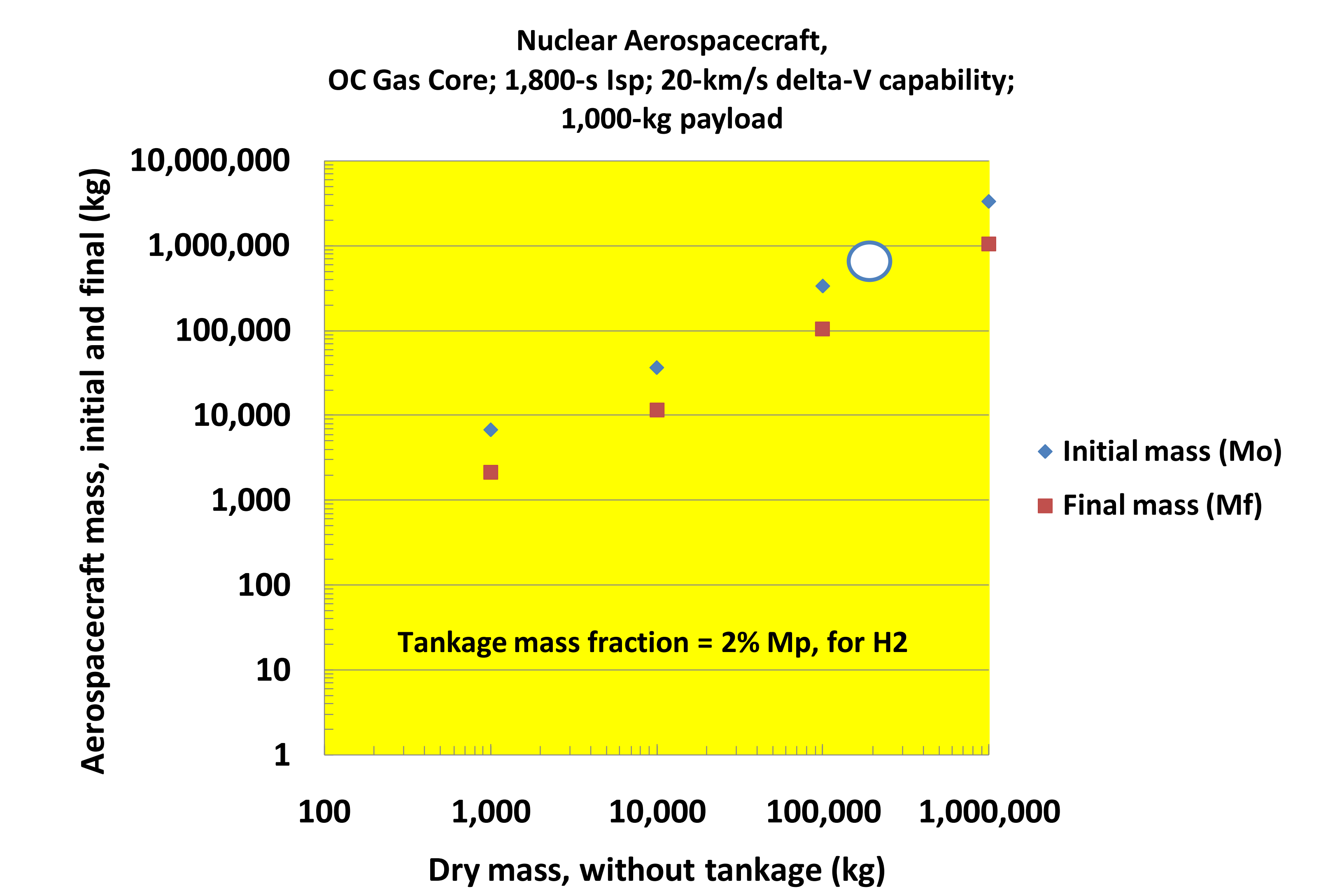
AMOSS GCR Designs



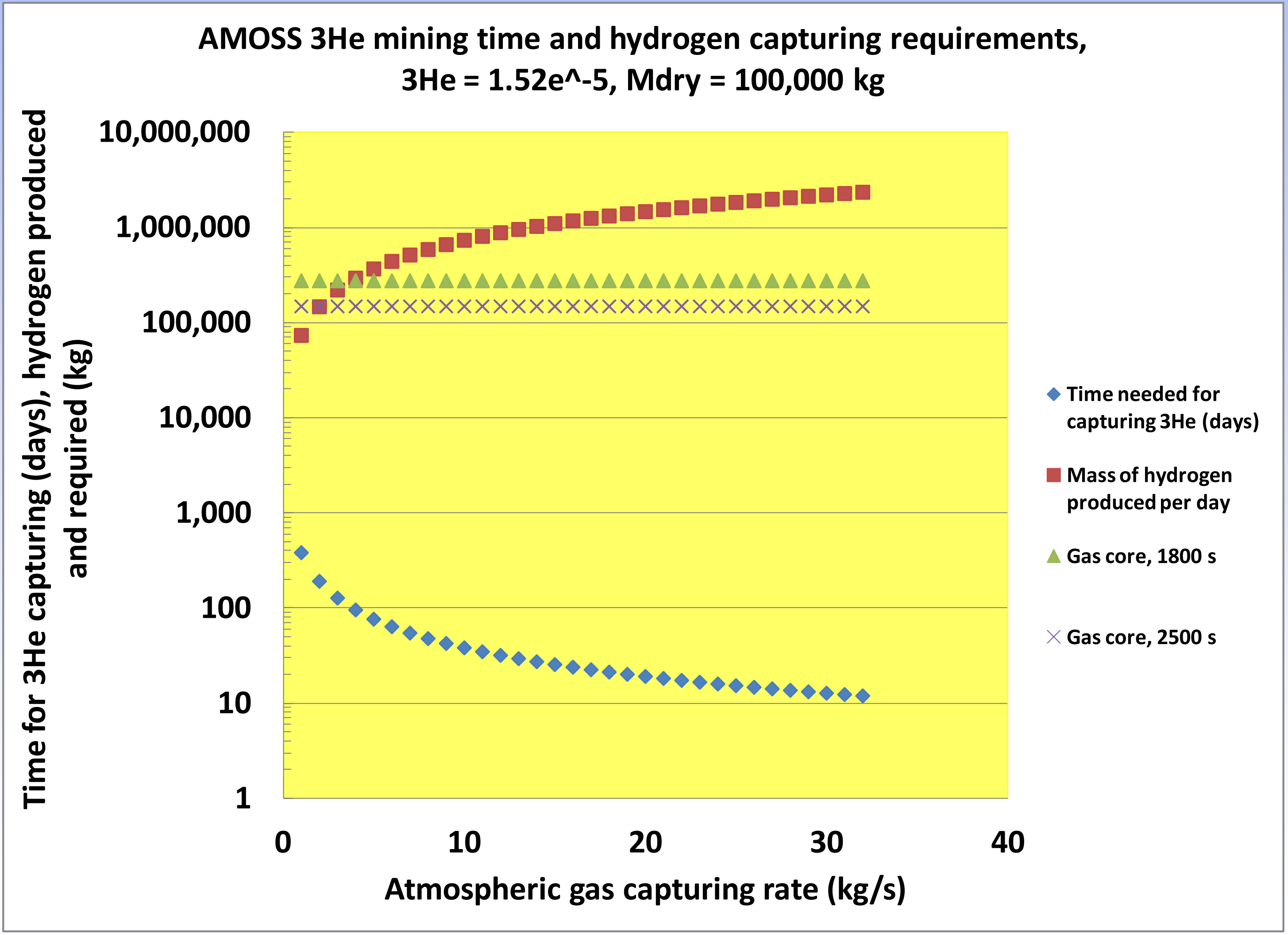
Gas Core Design and Analysis Overview

- Total aerospacecraft vehicle delta-V is 20 km/s.
- Single stage aerospacecraft.
- Gas core Isp values = 1800 and 2500 seconds
- Vehicles mass estimated over a broad range of dry masses.
- Dry mass (other than tankage) = 1,000, 10,000, 100,000, and 1,000,000 kg.
  - Typical gas core dry mass = 80,000 to 200,000 kg.
- Tankage mass = 2% and 10% of propellant mass.
- Comparative case: solid core NTP Isp = 900 seconds.

Gas core, Isp = 1,800 s, Tankage = 2% Mp



AMOSS, Hydrogen Production at Uranus



AMOSS Transportation Infrastructure and Implications – Uranus System Example

- Aerospacecraft (ASC) enter atmosphere and begins mining
- Lander(s) place the ISRU factories on moon(s).
- ISRU factory begins oxygen and hydrogen production.
- Lander is fueled with ISRU oxygen and hydrogen.
- Lander is loaded with hydrogen payload for OTV.
- OTV and lander rendezvous, OTV is fueled for round trip mission to Uranus.
- OTV picks up helium 3 from ASC.
- OTV delivers helium 3 to Lander (in moon’s orbit).
- Lander refuels OTV and delivers helium 3 to ISRU factory (PPack).

OTV "optimizations"

- Estimate OTV mass for all planet-to-moon round trip destinations.
- OTVs depart from 800 km planet altitude.
- OTVs arrive at moon(s), near moon's escape conditions (escape velocity).
- Will the smallest, or more distant moons provide the lowest OTV mass?
- Will the smaller or more distant moons require the longest OTV trip times?

Lander "optimizations"

- Estimate mass of all ascent-descent moon "escape" round trip destinations.
- Include gravity losses; 20% of escape delta-V.
- Added margin on delta-V and propellant included for return of the full payload mass, in case of unsuccessful rendezvous.

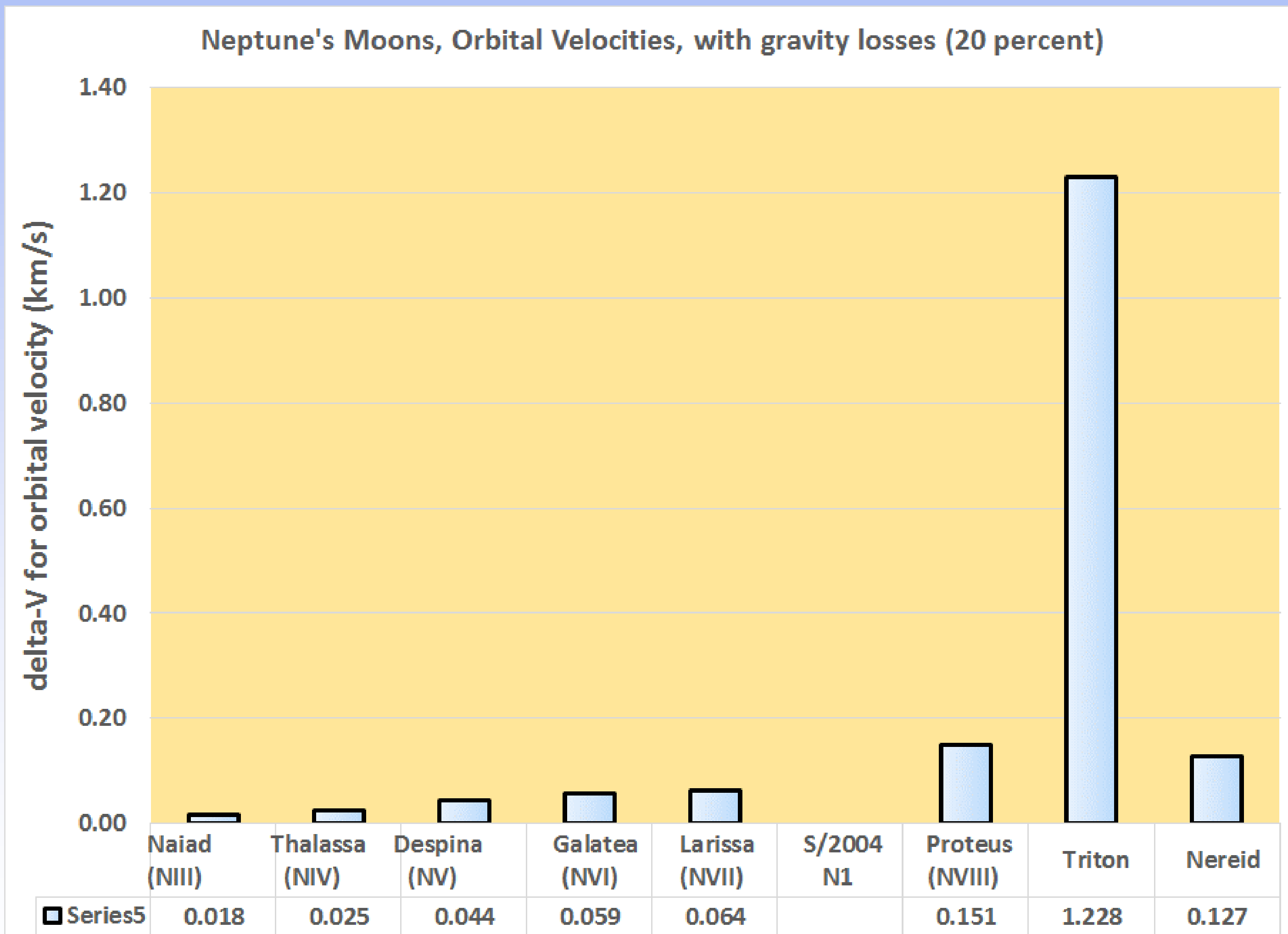
Lander delta-V, Uranus' Moons

	Moon	Round-trip delta-V (km/s)	delta-V Capability (km/s)	Sizing Category	
	Miranda (UV)	0.44	0.5	a	
	Ariel (UI)	1.34	1.4	b	
	Umbriel (UII)	1.24	1.3	b	
	Titania (UIII)	1.85	1.9	c	
	Oberon (UIV)	1.74	1.8	c	

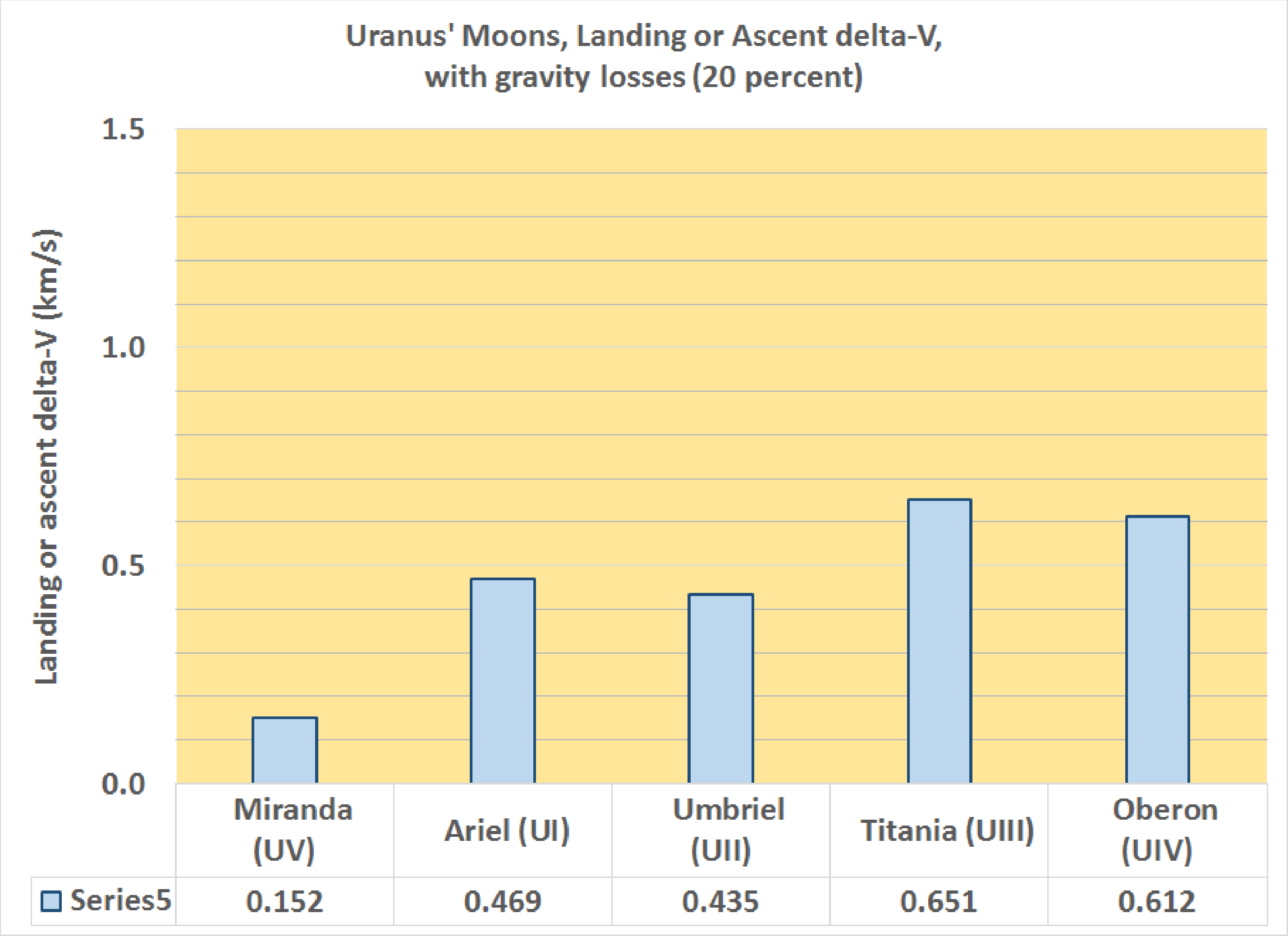
Lander delta-V, Neptune's Moons

Moon	Round-trip delta-V (km/s)	delta-V Capability (km/s)	Sizing Category
Naiad (NIII)	0.06	0.06	a
Thalassa (NIV)	0.08	0.08	a
Despina (NV)	0.13	0.14	b
Galatea (NVI)	0.17	0.18	b
Larissa (NVII)	0.19	0.19	b
S/2004 N1			
Proteus (NVIII)	0.44	0.50	c
Triton	3.49	3.50	d
Nereid	0.37	0.40	c

Lander delta-V, Neptune's Moons



Lander delta-V, Uranus' Moons

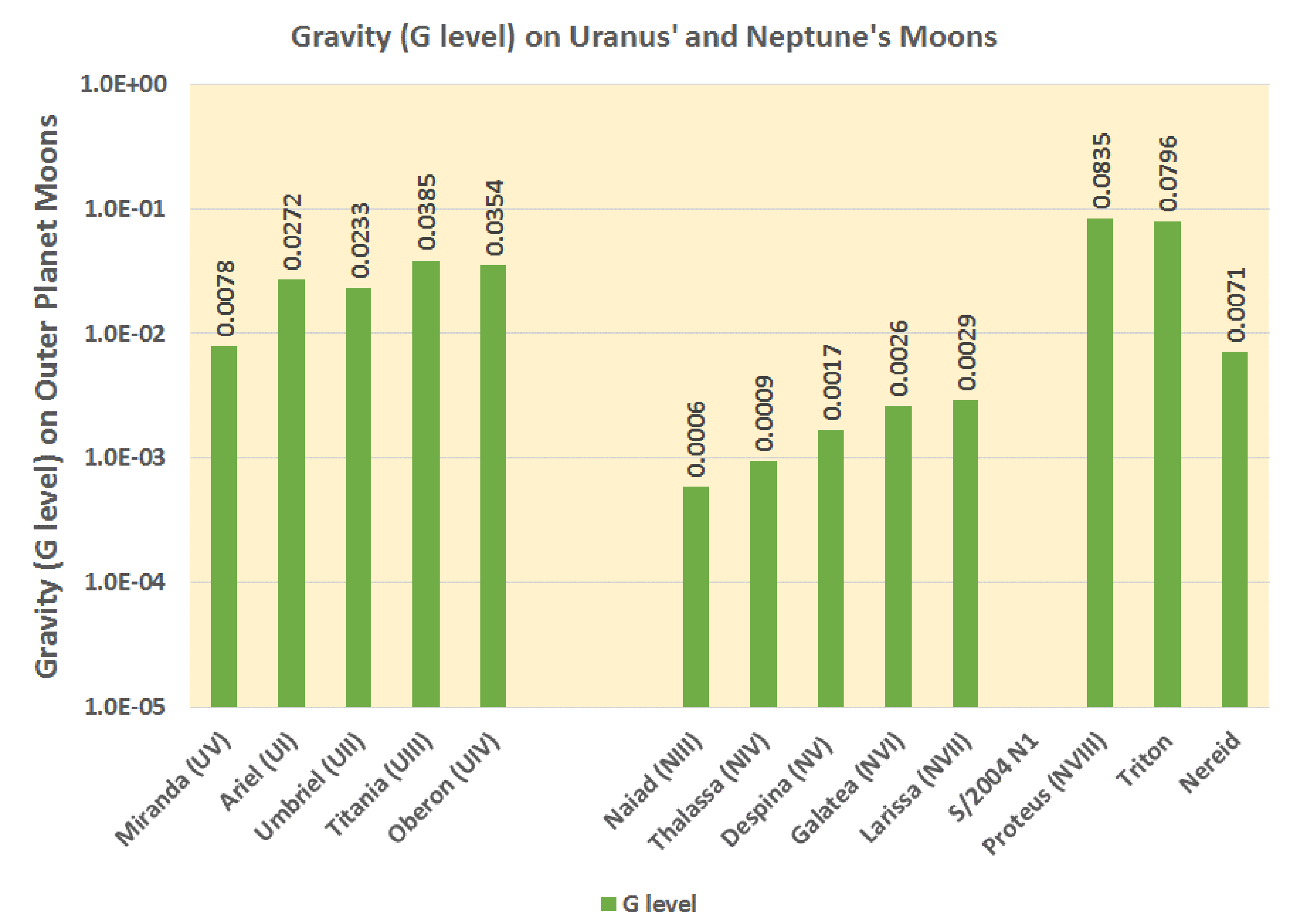


"Optimizations"

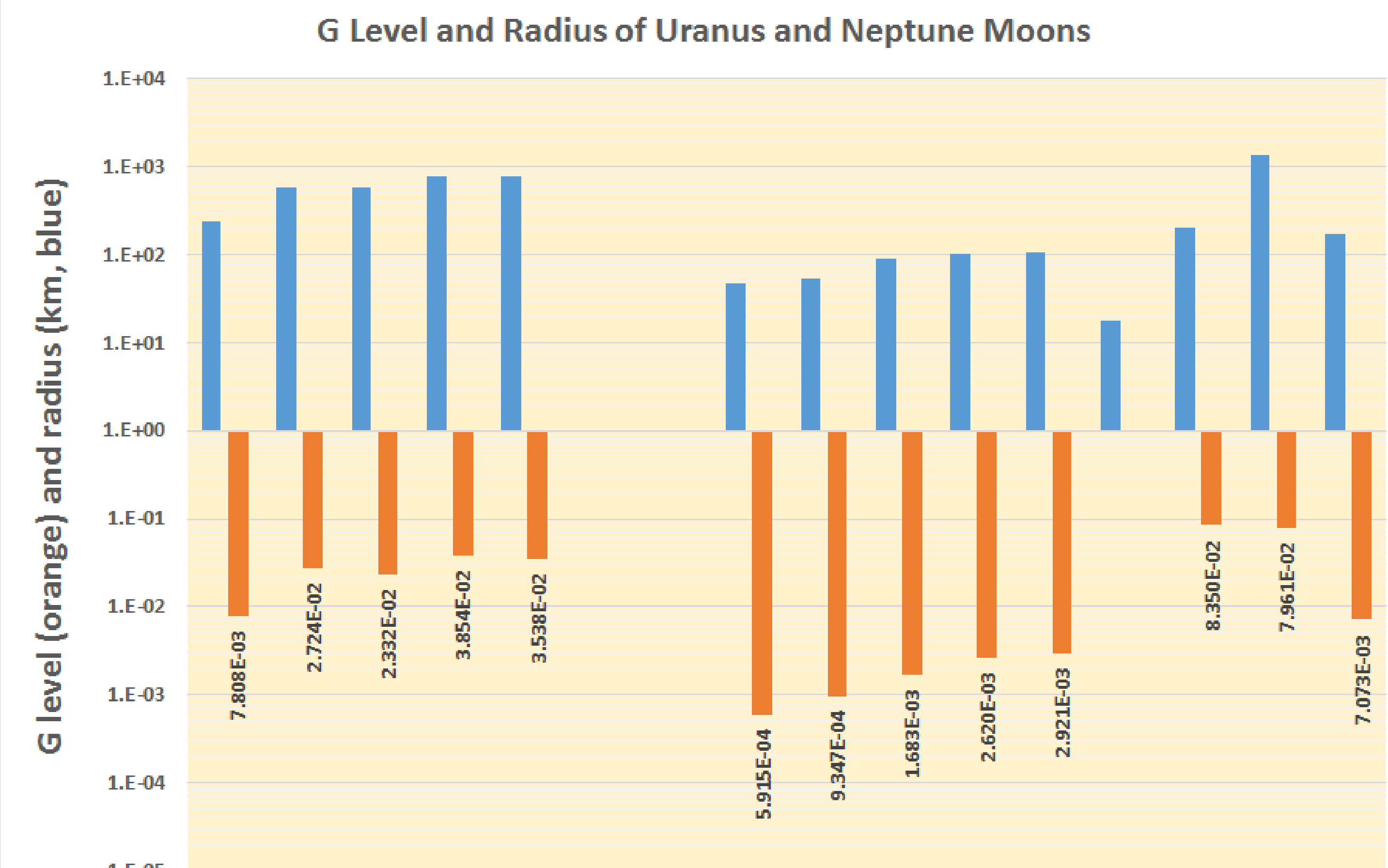
- Determine the best moon for operations.
- Is the smallest moon best?
- Does the smallest moon, with the lowest escape velocity, help in the optimization?
- Factory operations, lander fueling operations, and moon gravity level, for propellant and PPack factories may be the determining factors.

PPack = Physics package (NPP bomblets)
NPP = Nuclear pulse propulsion

Outer Planet Moon G Levels



Outer Planet Moon G Levels

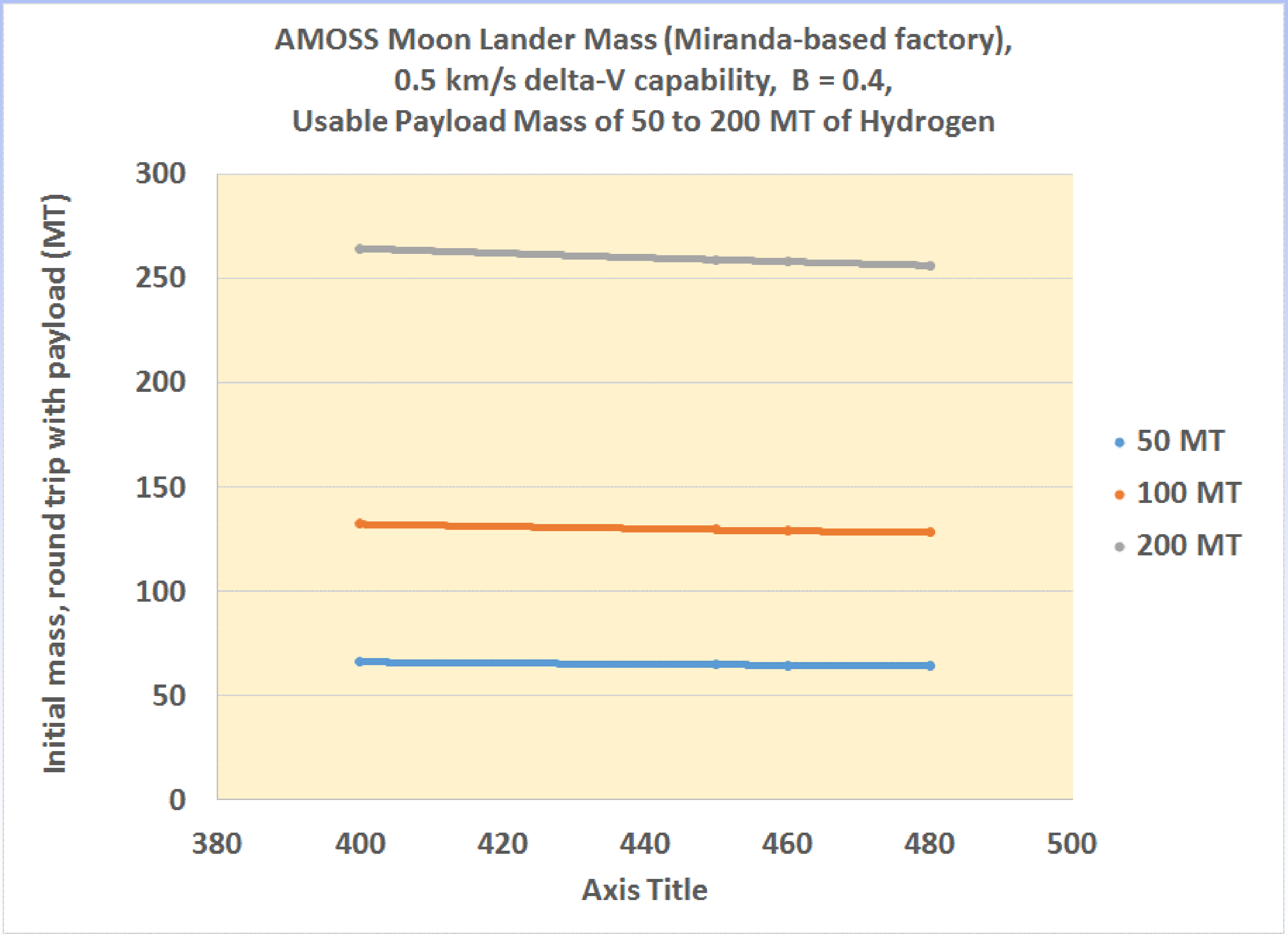


	Miranda (UV)	Ariel (UI)	Umbriel (UII)	Titania (UIII)	Oberon (UIV)	Naiad (NIII)	Thalassa (NIV)	Despina (NV)	Galatea (NVI)	Larissa (NVII)	S/2004 N1	Proteus (NVIII)	Triton	Nereid
R (km)	240	581	585	789	761	48	54	90	102	108	18	202	1,353	170
G level	0.008	0.027	0.023	0.039	0.035	0.001	0.001	0.002	0.003	0.003		0.083	0.080	0.007

Lander Design and Masses

- The lander's mission is to deliver hydrogen to the OTV and return to the moon with the helium 3 or deuterium payload(s).
- The round trip delta-V would be based on each moon's escape velocity.
- As an example, a 0.5 km/s delta-V value is needed for the moon, Miranda.
- Thus, the lander has the capability to reach escape conditions to rendezvous with the OTV.
- The lander was designed with an oxygen /hydrogen main propulsion system.
- The lander Isp was varied from 400 to 480 seconds. The dry mass scaling equation was:
  - Mdry, stage (kg) = Mdry, coefficient • Mp (kg)
  - Mdry, coefficient = 0.4

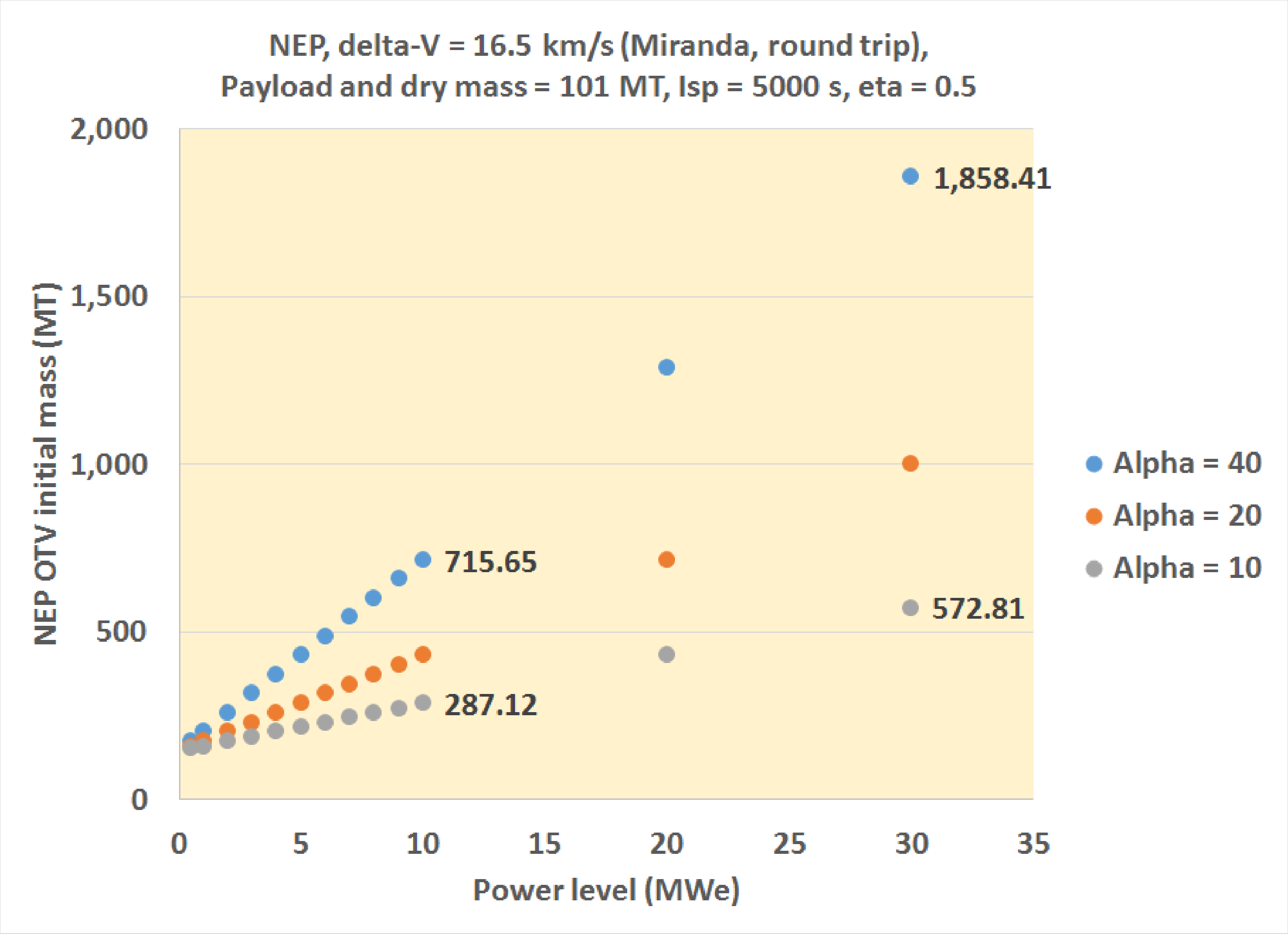
Moon Lander Mass, Miranda



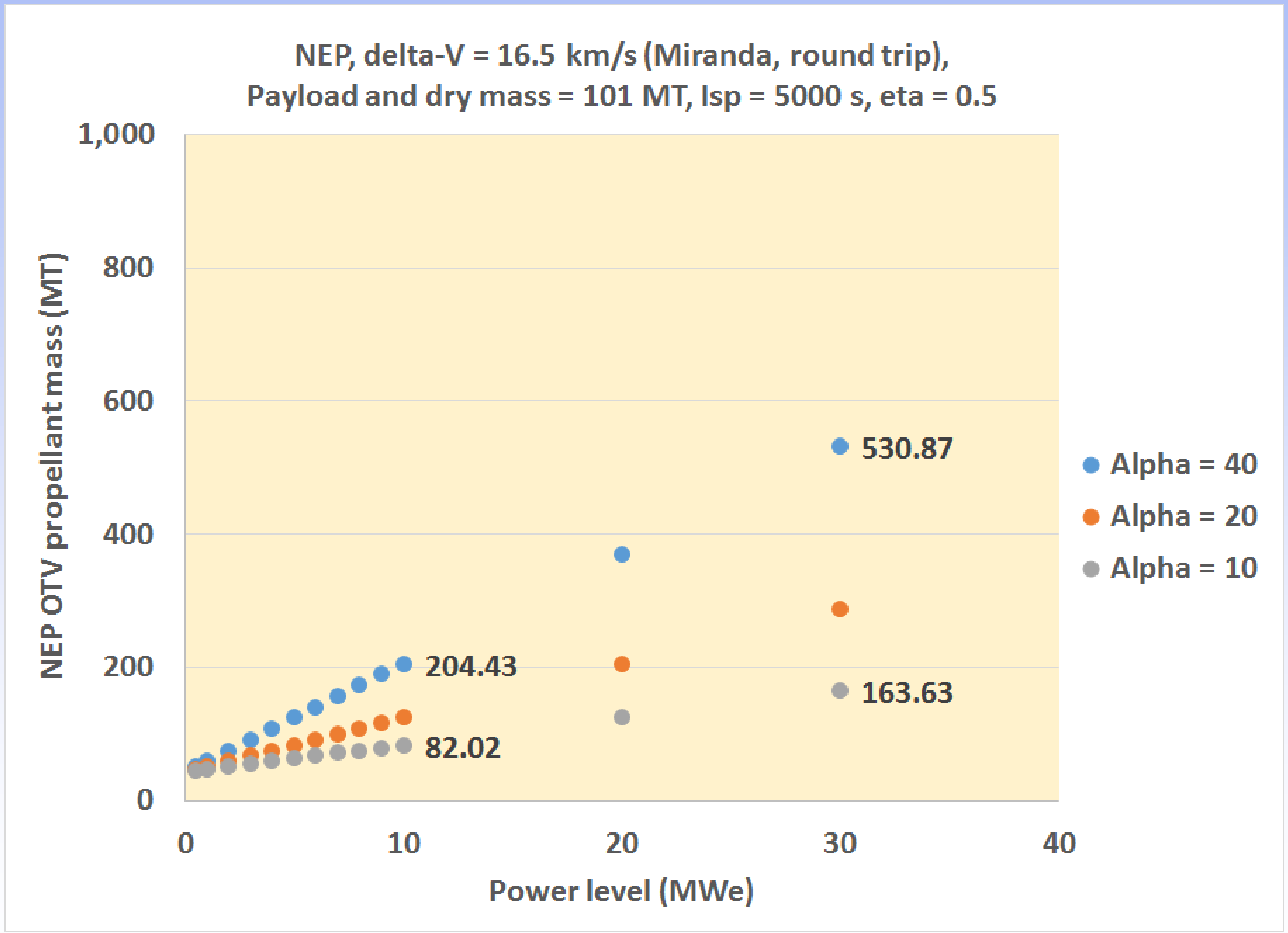
ISRU Factory Design Issues (need to update)

- The outer planet moons have low gravity levels.
- The gravity levels are similar to the disturbance accelerations of the ISS.
- Low gravity may require centrifuges for processing.
- The masses of the propellant factories must include mass estimates for low gravity operations.
- Cryogenic propellant processing and purification.
- PPack processing and assembly.
- Factory options.
  - Lightweight factory (all external storage and processing),
  - Heavy factory (also with external storage and processing),

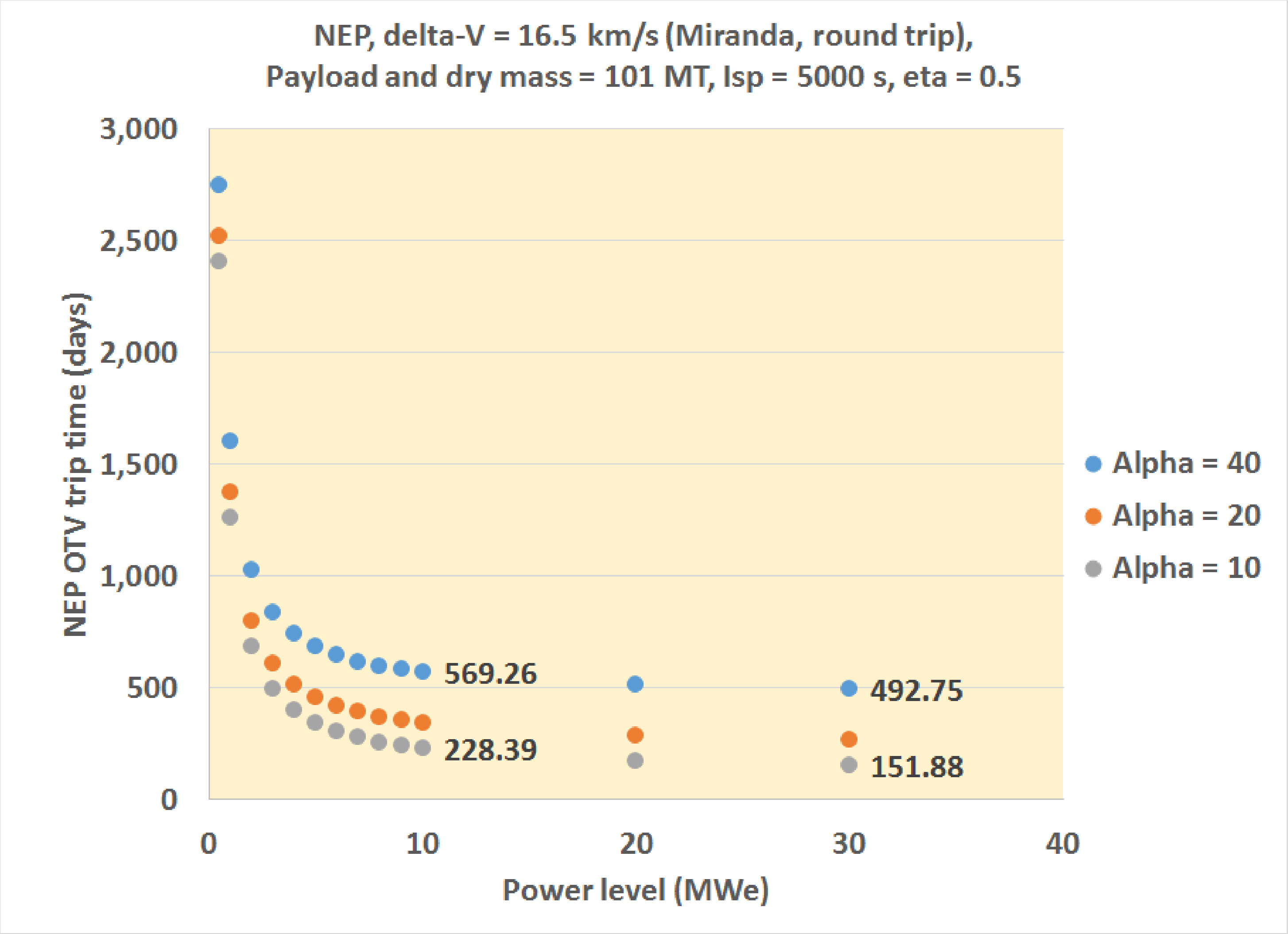
Outer Planet Moon OTVs, Landers (1/2)



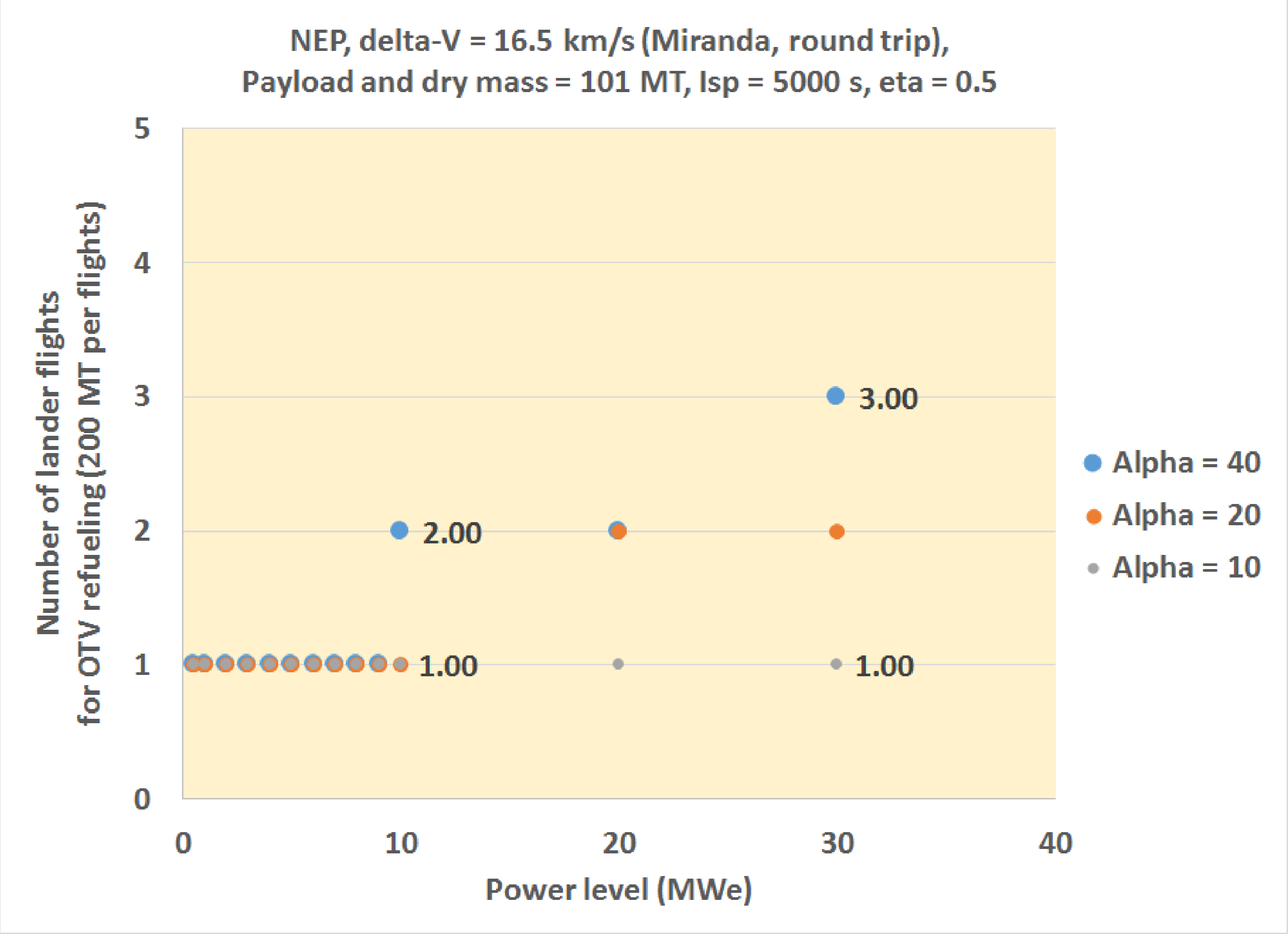
Outer Planet Moon OTVs, Landers (1/2)



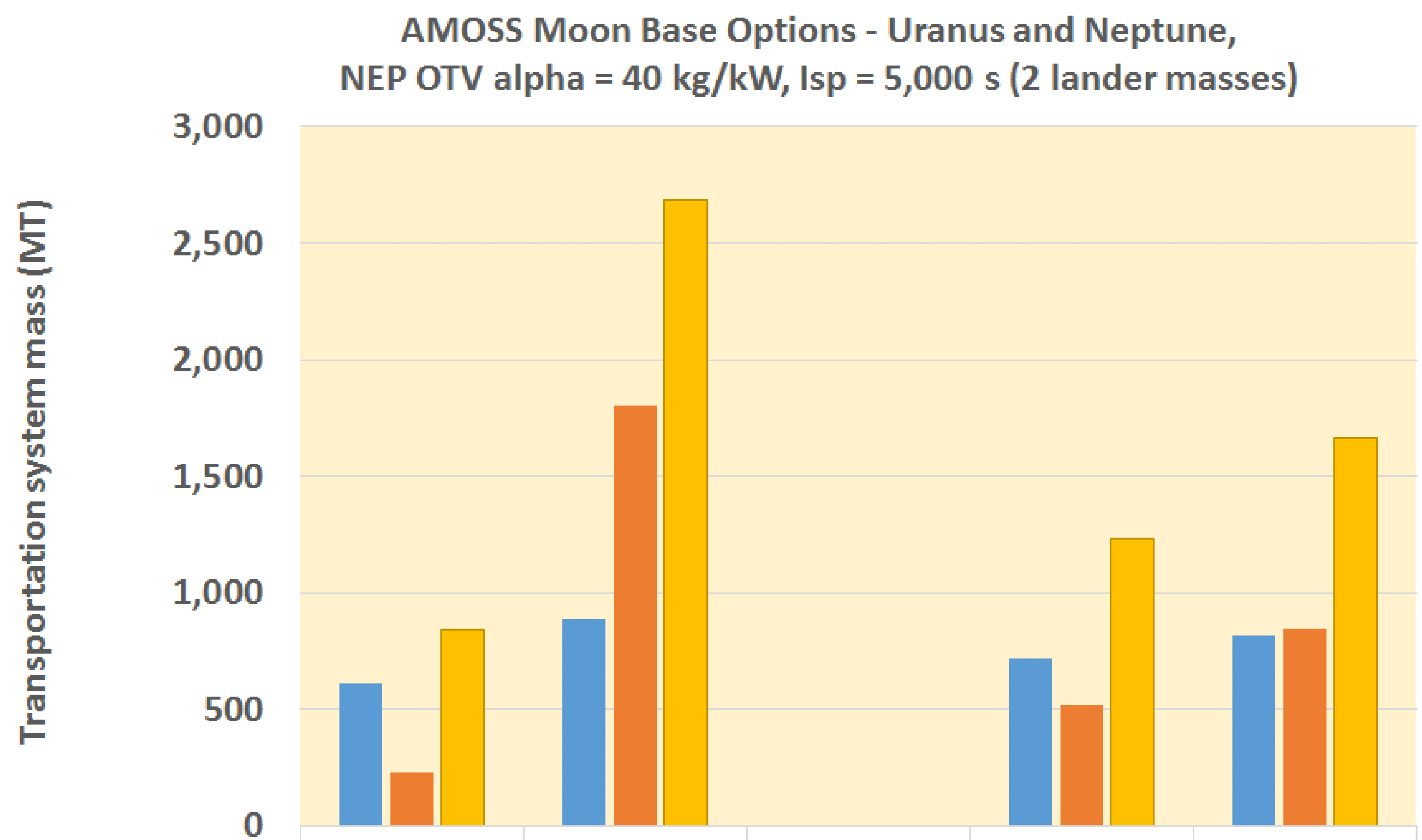
Outer Planet Moon OTVs, Landers (2/2)



Outer Planet Moon OTVs, Landers (2/2)

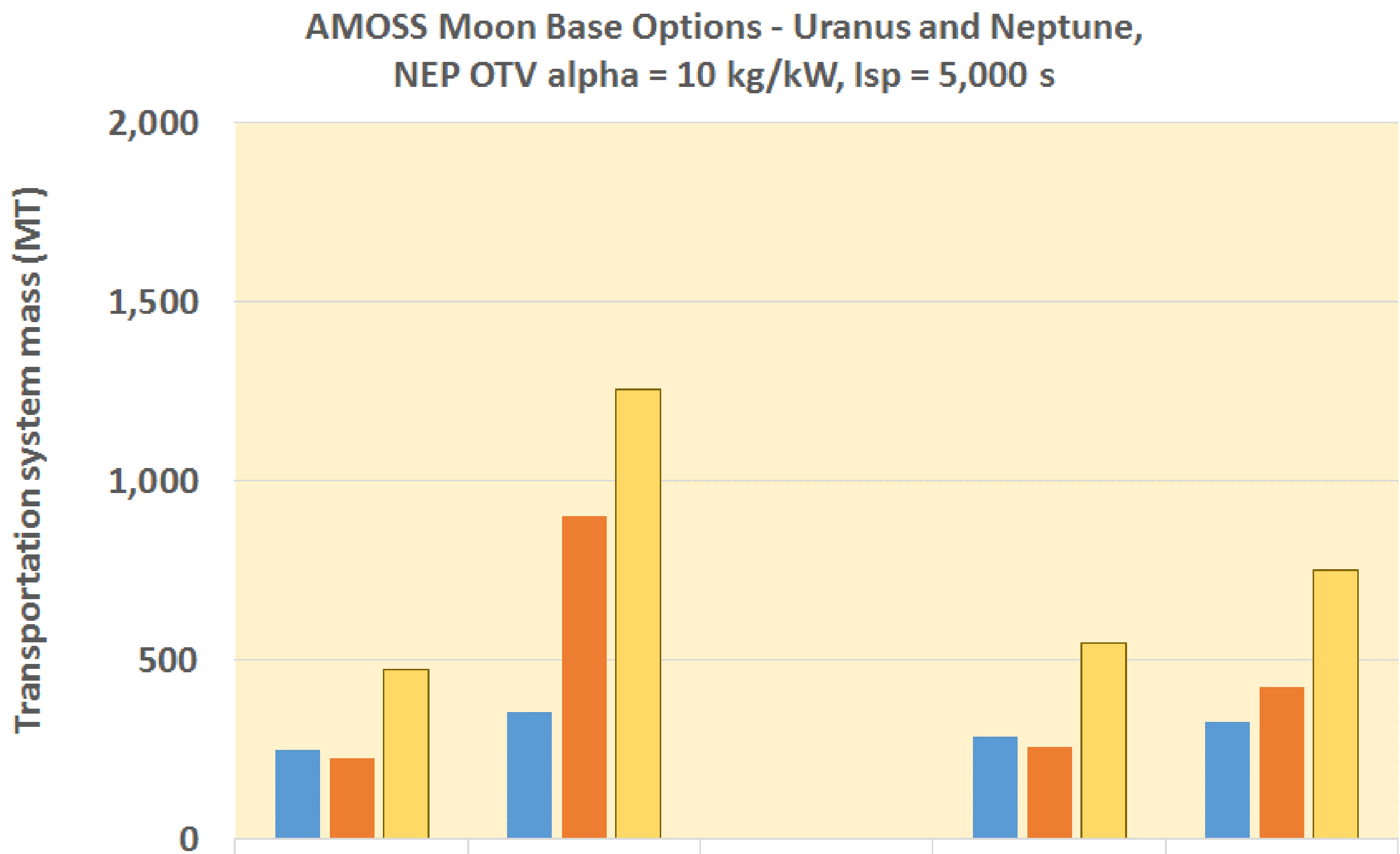


AMOSS Moon Transportation Masses (1/2)



	Thalassa	Triton		Miranda	Titania
OTV	613.3	886.0		715.7	814.6
2 Landers (460 s)	226.0	1,800.0		516.0	848.0
Total	839.3	2,686.0		1,231.7	1,662.6

AMOSS Moon Transportation Masses (2/2)



	Thalassa	Triton		Miranda	Titania
OTV	246.1	355.5		287.1	326.8
Lander (460 s)	226.0	900.0		258.0	424.0
Total	472.1	1,255.5		545.1	750.8

Preliminary Transportation Optimization (1/4)

- Establishing an optimum transportation system will be influenced by many factors: the OTV mass and power level, the payload mass of the lander and the selection of the moon for the mining factories.
- Several optima will be created based on the size and mass of the moon selected.
- The moon's mass will strongly influence the propellant mass needed for the refueling of its oxygen/hydrogen propulsion system and the time needed for creating the fuel for the OTV.

Preliminary Transportation Optimization (2/4)

- With the OTVs, the 10 MWe power level appears to be the most acceptable.
- The initial mass of the OTV with power levels of 20 and 30 MWe is too high, with no significant trip time benefits over the OTV at the 10 MWe power level.
- For the 101 MT dry mass case, at 10 kg/kWe, and at 5,000 seconds of Isp, the trip time for the 30 MWe level is 152 days versus 229 days at the 10 MWe level.
- With the 40 kg/kWe case (with the same Isp and dry mass), the trip time at 30 MWe is 493 versus 570 for the 10 MWe case.

Preliminary Transportation Optimization (3/4)

- The OTV trip times are a significant issue.
- Many flight times are 100's of days.
- Initially, a single 1 MT payload of helium 3 or deuterium would fly on each OTV flight.
- Multiple helium 3 or deuterium payloads will have to be manifested on the OTVs.
- While the OTV and the lander can rendezvous at the moon's escape conditions, it may be more stable to conduct the propellant and payload transfers at a high moon orbit, but not at or beyond the moon's escape conditions.

Preliminary Transportation Optimization (4/4)

- Lander payloads of 200 MT provide the minimal number of lander flights.
- The processing on the moon of the propellant, the propellant loading, and the cryogenic hydrogen payload loading may favor the largest payload capacity lander.
- With the 200 MT hydrogen payload, the number of lander flights needed to refuel the 21 MT dry mass (5,000 seconds Isp) OTV is 1 flight for the 10kg/kWe case and 2 flights for the 40 kg/kWe case.
- Landers might be further optimized by increasing their payload capacity, which would further reduce the number of flights.

Concluding Remarks (1/3)

- **Using outer planet moon bases for mining propellants for OTVs and landers is an important option.**
- **Storing the AMOSS nuclear fuels away from the atmosphere will minimize the potential for unanticipated deorbiting of the orbiting storage facility.**
- **Using the moons for storage of the nuclear fuels and base of operations for OTV refueling is an excellent option.**
- **Though the gravity of these moons are much lower than that of Earth, that gravity will likely assist in any processes for mining and fuel processing.**

Concluding Remarks (2/3)

- The 10 MWe power levels for the OTV seems best for providing a relatively short trip time.
- The OTVs and landers will rendezvous near the escape condition of the small moon, shortening the trip time for the OTV (eliminating the need to spiral into low moon orbit).
- Larger landers (of 200 MT payloads) are more attractive than small landers, as the large landers require fewer flights to resupply the OTVs with fuel.
- The OTV trip times may be too long for effective use of the more distant moons. Moons that are closer to the planet may be required.

Concluding Remarks (3/3)

- The gravity levels of the moons are very low.
- Therefore, artificial gravity may be needed to do effective ISRU processing.
- Processing in orbit may be more attractive for the PPack factories.
- Smaller moons that are closer to the planet require the lowest transportation system mass.
- The added complexity and mass of any large artificial gravity system may drastically change the optimization of any transportation system.

Neptune, Go ISRU

JPL